Quantum-Well States in Copper Thin Films

Directly Probing the Spatial Variation of the Wavefunction

Scientists from the University of California, Berkeley, and the Advanced Light Source (ALS) have combined precision sample-fabrication technology and the spatial resolution achievable with a high-brightness synchrotron-radiation source to make photoemission images of the spatial variation of electron wavefunctions (quantum-well states) in thin copper films. The images qualitatively verify a proposed model in which a longer wavelength "envelope" function modulates a shorter wavelength component of the wavefunction. Quantum-well states are believed to underlie the magnetic behavior of the layered metallic nanostructures now under intense development for advanced data storage and memory applications, so developing a quantitative understanding is a major thrust of magnetic materials research.

Wavefunction engineering refers to tailoring electron wavefunctions in magnetic nanostructures with layer thicknesses measured in nanometers in order to control the spin-dependent behavior of electrons. Some magnetic nanostructures are already in commercial production, such as high-sensitivity read heads in the newest data-storage disks. Based on the giant-magnetoresistance (GMR) effect, these read heads derive their sensitivity from a spin-dependent reflectivity of electrons at the layer interfaces. Expected in the not-too-distant future are high-speed, low-power, non-volatile magnetic random-access memories based on spin-dependent quantum tunneling between layers. If perfected, such devices would dramatically change the architecture of computer design.

In a simple model of electrons in a metal, an electron wavefunction can be represented by a short-wavelength component that is modulated by an envelope with a longer wavelength. In a large sample, the allowed electron energies fall into a series of bands within which the energy is quasi-continuous, but as the dimensions shrink, the allowed energies become widely separated and few in number. For a film, which is thin in only one direction, the energy is quantized in this way for travel perpendicular to the film surface and is continuous for travel parallel to the surface. For these discrete quantum-well states, the envelope functions are required to fit an integer number of half-wavelengths into roughly the film thickness.

The Berkeley group set out to visualize the envelope function by means of photoemission measurements of a copper film using a finely focused x-ray beam from the ALS to excite photoelectrons. The intensity in the photoemission spectrum oscillates with maxima occurring when the photoelectron energies match those of quantum-well states. The researchers used a layer of nickel only one atom thick embedded in the quantum well to probe the wavefunction. Embedding the nickel between two wedge-shaped copper layers oriented at right angles made it possible either to continuously vary the position of the nickel layer in a film of fixed total thickness or to keep the nickel layer fixed in the middle of a quantum well of continually varying thickness, depending on the direction of travel across the sample surface.

Measuring the photoemission intensity at a fixed electron energy corresponding to photoelectrons emitted from quantum-well states at the Fermi level of copper while scanning the x-ray beam across the sample resulted in a pattern of light and dark oscillations. The quantum-well states are least perturbed when the nickel layer is near an antinode of the envelope function. Therefore, scanning in the direction of fixed thickness and variable nickel position produced an image of the envelope with bright areas representing antinodes and dark areas nodes. Scanning in the direction corresponding to an increasing well thickness and fixed nickel position gave bright bands as additional quantum-well states became allowed in the thicker film.

The group intends to test its qualitative analysis with quantitative theoretical calculations with the hope of reaching a level of understanding that will turn wavefunction engineering in magnetic nanostructures into a practical tool.

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- **A new thin-film magnetics technology —"wavefunction engineering"**
  - *GMR read heads for high-density disk storage media are in production*
  - *High-speed, non-volatile magnetic random-access memory are expected*

- **Quantum wells in metallic thin films**
  - *Quantum-well states emerge when dimensions are small*
  - *Quantized energy and momentum*
  - *Wavefunction "envelope" plays major role*

- **Angle-resolved photoemission with wedge samples**
  - *Wedge samples vary quantum-well dimensions continuously*
  - *Photoemission detects quantum-well states*
  - *High brightness gives spatial resolution*

- **Experiments by UC Berkeley group at the ALS**
  - *Direct spatial visualization of the wavefunction envelopes*
  - *Foundation for "wavefunction engineering" of metallic layered systems*

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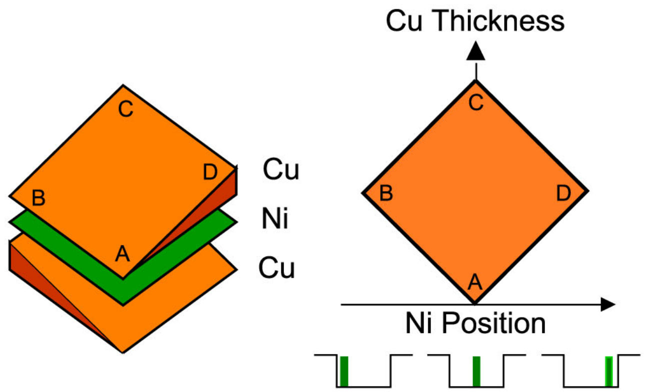

Double-wedge sample varies Ni-layer position in the horizontal direction and total Cu thickness in the vertical.

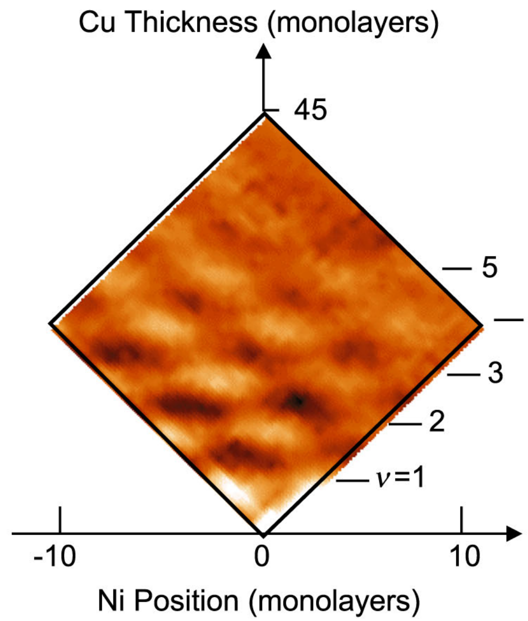

Image of the photoemission intensity at the Fermi level shows both horizontal and vertical variations.

The horizontal oscillations in the photoemission intensity map the spatial variation of the quantum-well envelope function, whereas the vertical intensity variation shows the presence of additional envelope modes (ν) as the quantum well thickness increases.

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